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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 : G01S 1/02	A1	(11) International Publication Number: WO 98/0072 (43) International Publication Date: 8 January 1998 (08.01.9

(21) International Application Number: PCT/US97/11409

(22) International Filing Date: 26 June 1997 (26.06.97)

(30) Priority Data:
60/020,845 28 June 1996 (28.06.96) US

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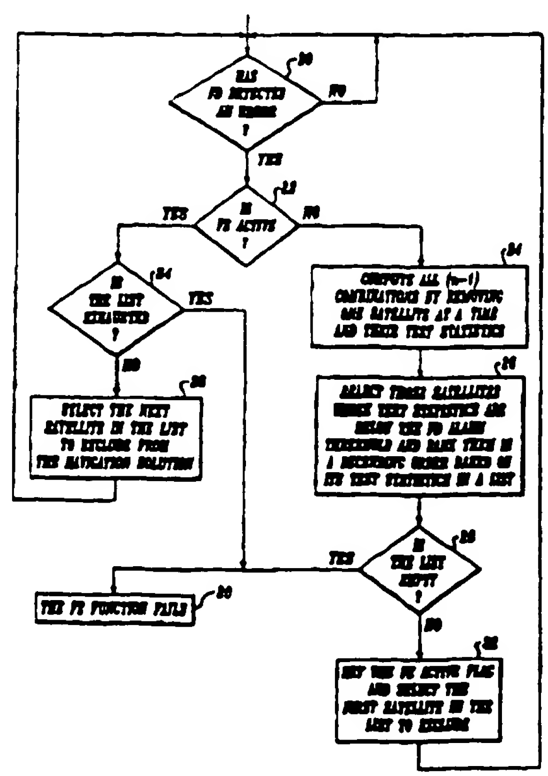
(81) Designated States: DE, European patent (AT, BE, CH, D DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
Before the expiration of the time limit for amending th claims and to be republished in the event of the receipt amendments.

(54) Title: FAULT DETECTION AND EXCLUSION USED IN A GLOBAL POSITIONING SYSTEM (GPS) RECEIVER

(57) Abstract

A fault exclusion (FE) system for a global positioning system (GPS) receiver which upon detection of a faulty satellite, for example, by a fault detection (FD) system, such as a receiver autonomous integrity monitoring (RAIM) system. The FE system computes the test statistics for all satellites and ranks the satellites in descending order of their test statistics. The FE system excludes data from the satellites one at a time starting with the satellites at the top of the list. Should a subsequent satellite anomaly be detected, the FE system excludes satellites based on the test statistics computed for the previous satellite anomaly condition. The FE system proceeds down the list until the fault detection condition is cleared or the list is exhausted without affecting the availability of the FD system.



FAULT DETECTION & EXCLUSION USED IN A GLOBAL POSITIONING SYSTEM (GPS) RECEIVER

This application is based upon and claims priority of U.S. Provisional Application Number 60/020,845, dated June 28, 1996.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a fault exclusion (FE) system for a global positioning system (GPS) receiver and more particularly to an FE system that upon detection of a fault, for example, by a fault detection (FD) system, such as a receiver autonomous integrity monitoring (RAIM) system, computes test statistics for all of the possible subsets of satellites, removing one satellite at a time. The test statistics for each of the subsets are ranked in decreasing order in a list. The subsets with the lowest test statistics below a test statistic threshold are used to exclude a faulty satellite. Should a subsequent fault be detected indicating that the test statistic exceeds the threshold at a later time, due to, for example, changing geometry, the FE system utilizes the previously determined list of test statistics to exclude a satellite.

can cause incorrect position data to be transmitted to the GPS receivers. When a satellite anomaly is detected, a warning is generated to enable another on-board navigation system to used or the faulty satellite to be excluded from the navigational solution. The RAIM system is discussed in detail in "Understanding GPS Principles an Applications", Artech House Publishers, 1996, pages 306-314; and "A Baseline GPS RAIM Scheme and a Note on the Equivalence of Three RAIM Methods", by R. Graver Brown, Journal of the Institute of Navigation, Vol. 39, No. 3, Fall 1992, pages 301-315, hereby incorporated by reference.

Normally at least five satellites or four satellites and an altitude input are required. The RAIM system detects incorrect position data from a particular satellite using a least squares residual (LSR) method by cross checking the residuals of the pseudorange measurements for the suspect faulty satellite with at least five other satellites or four other satellites and an altitude input. Using the LSR method, five equations for four unknowns (east, north, up aircraft position and aircraft receiver clock bias). Since five equations are used to solve for four unknowns, the system is considered to be overdetermined. GPS systems are also disclosed in U.S. patent nos. 5, 202,829; 5,317,514 and 5,436,632.

Such systems are known to require six or more satellites in order to provide acceptable position data. In order to determine if any of the satellites are providing faulty positional data, a test statistic threshold is computed. The test statistic of the system is then compared with the test statistic threshold. Any time the test statistic exceeds the test statistic threshold a faulty satellite is indicated. Upon detection of a faulty satellite, one satellite at a time is removed from the navigational solution. Test

satellites one at a time, starting with the satellites at the top of the list, proceeding down the list until the fault detection condition is cleared or the list is exhausted.

DESCRIPTION OF THE DRAWINGS

These and other objects of the present invention will become readily understood with reference to the following specification and attached drawings wherein:

- The sole figure is flow diagram of the fault exclusion system in accordance with the present invention.

DETAILED DESCRIPTION

The present invention relates to a fault exclusion (FE) system for a global positioning system (GPS) receiver which provides improved availability of the system. When incorrect navigational data is detected by a fault detection (FD) system, such as a receiver autonomous integrity monitoring (RAIM) system, the FE system in accordance with the present invention utilizes the test statistics previously computed for the last satellite anomaly condition in order to decide which satellite to exclude.

The RAIM system, as discussed above, is a self-contained integrity monitoring system which provides a warning when a GPS satellite anomaly is detected. Upon detection of a satellite anomaly by the FD system, the FE system excludes the data from the satellite providing the incorrect navigational data from the navigation solution according to criteria discussed below to enable the GPS to continue to be used as the primary navigational system. The RAIM system uses an overdetermined solution to detect a satellite anomaly and thus requires at least five satellites (up to eight satellites), or four satellites plus an altitude input.

$$A = \begin{bmatrix} -U_{1x} & -U_{1y} & -U_{1z} & 1 \\ -U_{2x} & -U_{2y} & -U_{2z} & 1 \\ -\tilde{U}_{nx} & -U_{ny} & -U_{nz} & 1 \end{bmatrix}$$

where, the components U_n are the components of the line of site vector from the n^{th} satellite.

To have a good detection probability, the $dHDOP_{max}$ must meet the criteria set forth in equation (2).

$$dHDOP_{max} < \frac{\epsilon_{max}}{\sqrt{T}+3\sigma} \qquad (2)$$

where

T is the threshold of the test statistic used in the RAIM LSR analyses; σ is the deviation of the standard availability (SA) and receiver losses; and ϵ_{max} is the maximum allowable position error.

Alternatively, the $DHOP_{max}$ threshold may be determined as set forth below as generally described in: "GPS RAIM: CALCULATION OF THRESHOLDS AND PROTECTION RADIUS USING CHI-SQUARE METHODS-A GEOMETRIC APPROACH", by R. GROVER BROWN, RTCA Paper No. 491-94/SC 159-584, hereby incorporated by reference. In this method, the $dHDOP_{max}$ threshold is determined by Monte Carlo simulation based upon a miss detection rate and the number of satellites in view. The simulation is based upon a miss detection rate of 0.001 with an optimal 21 satellite constellation using the worst case in the most difficult satellite to detect. Points are sampled every 3 degrees of latitude and 180 nautical miles in longitude. Each point is sampled, for example ever 5 minutes for 12 hours. Typical $dHOP_{max}$ thresholds for

The test statistic (ts) is not normalized in equation (6). When no fault is present, the statistical distribution of the test statistic (ts) is independent of geometry which means that the solution for the test statistic (ts) is non-singular. If the test statistic (ts) is normalized by the square of the deviation (σ^2) the test statistic (ts) will have a chi-square distribution with n-4 degrees of freedom. The chi-square distribution function with n degrees of freedom is provided by equation (7):

$$f(x) = \frac{1}{2^{n/2}\Gamma(n/2)} x^{(n/2)-1} \epsilon^{-x/2}; \ for\ x > 0 \tag{8}$$

for x>0 where Γ is the gamma function as set forth in equation (8).

$$\Gamma(t) = \int_0^\infty x^{t-1} \epsilon^{-x} dx \tag{9}$$

The test statistic (ts) is independent of satellite geometry. The value of deviation σ is defined as the combination of selective availability (SA) and receiver noise; $\sigma_{SA} = 32.5$ and $\sigma_{RCVR} = 15$. The receiver noise may be averaged over 4 samples. As set forth in equation (9), the net contribution of receiver noise deviation σ_{RCVR} 7.5.

$$\sigma_{RCVR} = 15/\sqrt{4} = 7.5m \tag{14}$$

(FE) system excludes the data of the satellite with the anomaly from the navigation computations to enable continued use of the GPS as a primary navigation system.

The FE system requires at least six satellites or five satellites and an altitude input for proper operation. The availability of the FE system is checked, for example, at a 1 Hz rate; the same as the FD system. The FE system is thus able to exclude faulty satellite data without affecting the availability of the FD system which requires five satellites or four satellites and an altitude input as discussed above.

Upon detection of a satellite anomaly from the FD system, the FE system ranks each satellite by its test statistic (ts) in descending order and maintains a list of satellites whose test statistics (ts) are below the threshold. The FE starts at the top of the list and excludes data from the corresponding satellites one at a time going down the list until the FD system no longer detects a satellite anomaly (i.e., the test statistic is less than the test threshold). Should the list become exhausted, the loss of the FE system is indicated.

An important aspect of the invention relates to the condition when a subsequent satellite anomaly is detected. Rather than recalculate the test statistics as discussed above for all of the satellite subsets, the previously removed satellite is re-inserted into the navigational solution. The system then selects the satellite subset using the list of test statistics calculated for the previous satellite anomaly.

Referring to FIG. 1, the system first checks in step 20 whether the FD system, for example, the RAIM system discussed above, detected a satellite anomaly. Since the FE system only functions when a satellite anomaly is detected by the FD system, the FE system loops back to step 20 and waits for a satellite anomaly to be detected. If a satellite anomaly has been

was set in step 32, indicating a previous satellite anomaly and a satellite anomaly is currently detected by the FD system, the FE system utilizes the list of test statistics computed for the previous satellite anomaly and determines if the list is exhausted in step 34. If so, the system proceeds to step 30 and indicates a FE system failure. If not, the system proceeds to step 36. In this step the previously excluded satellite is re-inserted. The system then proceeds down the list computed in step 26 for the previous anomaly and selects the satellite subset with the next lowest test statistic in order to select a satellite to exclude. The system then loops back to step 20 to determine if the test statistic for the satellite subset selected in step 36 is less than the test statistic threshold. If so, the system loops back to step 20. If not, the system proceeds to steps 22 and 34 and selects another satellite to exclude based on the list computed in step 26. The system repeats this cycle until the list is exhausted or the test statistic becomes less than the test statistic threshold.

Obviously, many modifications and variations of the present invention are possible in light of the above teachings. Thus, it is to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described above.

What is claimed and desired to be secured by Letters Patent of the United States is:

6. A fault exclusion system for use with a detection system which detects satellite anomalies for GPS receiver for excluding data from a satellite providing incorrect navigational data, the system comprising:

means for computing the test statistics for a predetermined number of satellites; and

means for excluding data from satellites as a function of the test statistic for a previous satellite anomaly condition.

7. The fault exclusion system as recited in claim 6, further including means for ranking the satellites in descending order according to the computed test statistics.

8. The fault exclusion system as recited in claim 7, further including means for comparing said test statistics with a predetermined threshold and maintaining a list of satellites whose test statistics are less than said predetermined threshold.

9. The fault exclusion system as recited in claim 6, further including means for enabling said fault exclusion system only when said fault detection system has detected a satellite anomaly.

10. The fault exclusion system as recited in claim 7, wherein said fault exclusion system is only enabled when a predetermined number of satellites are available.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/11409

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01S1/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	LEE Y C: "RECEIVER AUTONOMOUS INTEGRITY MONITORING (RAIM) CAPABILTY FOR SOLE-MEANS GPS NAVIGATION IN THE OCEANIC PHASE OF FLIGHT" 500 YEARS AFTER COLUMBUS - NAVIGATION CHALLENGES OF TOMORROW, MONTEREY, CA., MAR. 23 - 27, 1992, no. -, 1 January 1992, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, pages 464-472, XP000344339 see the whole document	1-3,5-10
A		4

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[X] Further documents are listed in the continuation of box C

[X] Patent family members are listed in annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

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Date of the actual completion of the international search	Date of mailing of the international search report
22 October 1997	03.11.97

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Van Dooren, G

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intc. . . Application No
PCT/US 97/11409

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5317514 A	31-05-94	NONE	